K-Ar DATING OF QUATERNARY BASALTS

ZION NATIONAL PARK

UTAH

Terrie Winnett

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John F. Sutter

Dr. John F. Sutter
Senior Thesis Advisor

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INTRODUCTION

This project was designed to evaluate the merits of several sample preparation techniques used in dating Quaternary basalts by the conventional potassium-argon method. An attempt was also made to obtain some meaningful ages for such samples from the lava fields in and around Zion National Park, Utah.

A preliminary petrographic examination of Zion basalt samples collected by Dr. Wayne Hamilton of the National Park Service was made with the guidance of Dr. David Elliot. This was done in order to get a general idea of the nature of these basalts-- general degree of weathering, alteration, glass content, grain size. During the summer of 1977, samples were collected from flows or flow sequences whose ages, or at least relative ages, had been estimated by differential weathering (Nielson, 1976 and Threet, 1958) or stream downcutting (Hamilton, personal communication, 1977). Thin sections were prepared from these rock samples to discover whether or not they were suitable for dating. Their petrography is described in section III.

The sample preparation techniques, described in section IV, reflect the attempt to find a method which can deal effectively with the problems of dating a young basalt. The major concern is obtaining a percentage of radiogenic ^{40}Ar which is large enough to allow its accurate calculation. The low potassium content and the youth of these volcanic rocks make the absolute amount of their radiogenic ^{40}Ar small. Moreover, this problem is compounded by the introduction of relatively large amounts of atmospheric ^{40}Ar (i.e., dilution). It must be pointed out that no attempt was made to sytematically date a flow, per se, but only to get a good indication of its age by dating a part of that flow. Only one sample from each unit was collected, in contrast to the practice of collecting widely-spaced samples in order to accurately date a flow. Most of the analytical effort was concentrated on technique feasibility and the reproducibility of experimental results (as a reflection of those techniques or of internal consistency of a single sample).

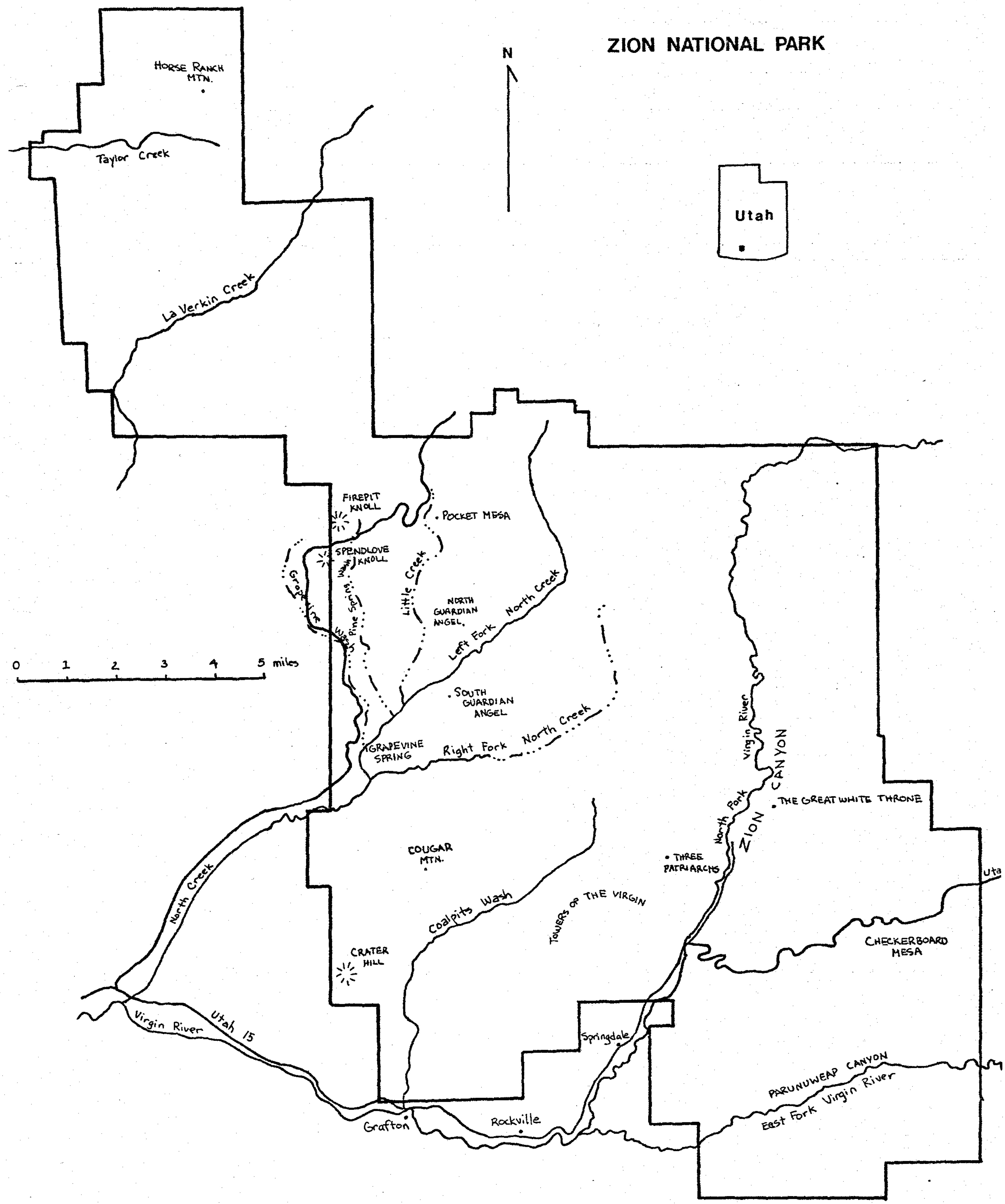

Figure 1 Zion National Park, Utah

GEOLOGIC BACKGROUND

Zion National Park is located in the southwestern part of Utah near the western edge of the Colorado Plateau province (Figure 1). Within the southwestern Colorado Plateau province, one of the outstanding regional features is a step-like series of cliffs and plateaus. In the Zion area one of the escarpments of this series is represented by the White Cliffs of Navajo Sandstone, which trend approximately northwest to southeast through the park and mark the southern edge of the Kolob Terrace. The other major geological feature is a north-south-trending fault system, which includes the Hurricane Fault west of Zion. This system of extensional faults was active during the basaltic volcanism in southern Utah, but the volcanic vents are not located along the faults (Hamblin, 1965). However, Threet (1958) states that all of the vents of Zion, except Crater Hill, appear to be located along joints. Hamblin believes that the attitude of these high-angle fault planes become more gentle with depth, making the fractures shallower than expected. High heat flow is detected in the area and peridotite inclusions have been found in some of the basalts. This information combined with the evidence for uplift, extensional faulting, and basaltic volcanism which was not fault-controlled led Best and Hamblin (1970) to theorize that a mantle plume was responsible for this activity. That is, rising magmatic material controlled the crustal response, rather than the fractures merely channeling magma. Also, the basalt types found in this area are unlike those found in the rest of the western U.S., but are more similar to those found in similar tectonic areas, such as Japan and eastern Australia (Leeman and Rogers, 1970).

Four flows or flow sequences were sampled (Figure 2): (1) the Crater Hill flow(s), located north of Grafton; (2) the flow sequence located above Grapevine Spring (these appear to be the same as the basalts found in Cave Valley and the North Creek Valley); (3) the Lee Valley flow southeast of Spendlove Knoll; and (4) the Pine Valley flow south of Pocket Mesa. Some may be expressions of the same episode, but they will be described here as separate units. Descriptions are based on field observation, personal communication with Dr. Wayne Hamilton, and field relations as shown on a pre-publication copy of the Zion Natural History Association geology map by Wayne L. Hamilton (Figure 2 was used to show the sample locations because it includes parts of lava fields which lie outside the park, but it does not show the same amount of detail as Hamilton's map). The flows were extruded onto sediments of the Shinarump, Moenkopi, and Temple Cap (formerly the upper member of the Navajo Sandstone) formations.

The Crater Hill flow was described by Gregory (1950) as several distinct flows of different ages and from multiple vents, but Threet (1958) refutes his argument, explaining the flow margins and differentiation as plausible results of a single episode of volcanism. He estimated the age of the flow at a few thousands to a few tens of thousands of years. Nielson (unpublished Master's thesis, 1976) has differentiated the Crater Hill basalts according to the geomorphic system described by Hamblin (1970). One of the objectives of this study is to determine whether the age difference, if it exists, is discernible. This flow can be seen as cap rock north of Utah State Highway 15, west of Grafton. These basalts rerouted the bed of the Virgin River south to its present location. Crater Hill itself, probably represents the last phase of volcanism in that area; the flow associated with it is very vesicular

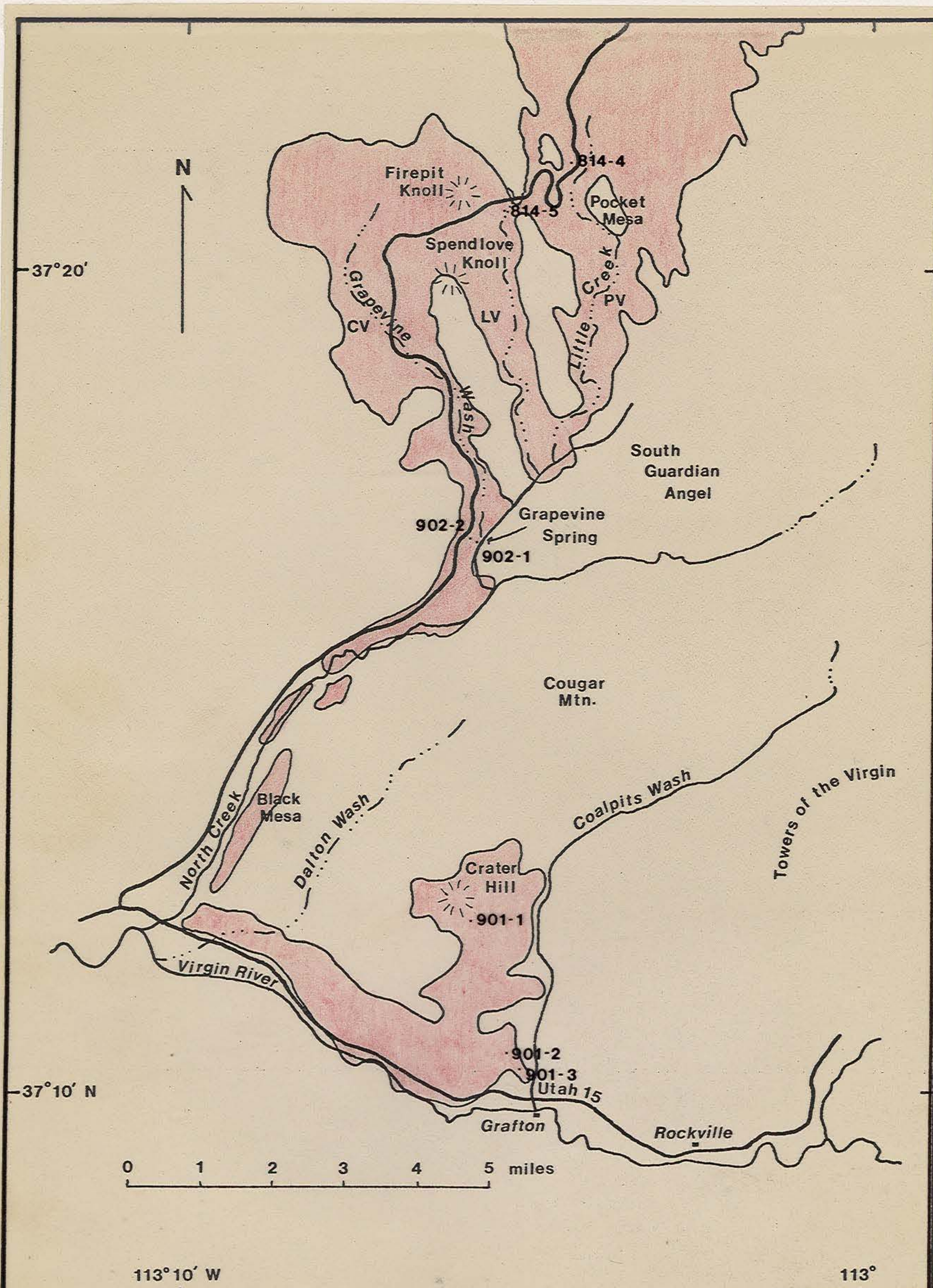

Figure 2 Location of basalt flows in Zion National Park area; sample sites indicated on overlay. After Gregory (1950).
CV=Cave Valley LV=Lee Valley PV=Pine Valley

and has a ragged surface.

The basalts of Lee Valley and Cave Valley, including those found in Grapevine Wash and North Creek seem to be of similar age as evidenced by comparable stream profiles (Hamilton, pers. comm., 1977). Hamilton estimated the age of the North Creek flows at about 250,000 years B.P. Their extent of dissection is similar and they may be related to the volcanism which formed Firepit and Spendlove Knolls.

The Pine Valley flow, from which no samples were dated, appears to be older than the Lee and Cave Valley flows. It is more dissected, and near the junction of Little Creek and the Left Fork of North Creek, the Lee Valley (Grapevine Wash) flow laps up on it at a lower elevation than the upper edge of its margin (Hamilton, pers. comm., 1977).

K-Ar DATING OF YOUNG BASALTS

Potassium-argon dating of samples from the Zion basalt flows posed problems, especially because they are so young. The reason for these problems can be better understood when the technique for measuring argon is considered. The mass spectrometer is used to measure the quantity of ^{36}Ar, ^{38}Ar, and ^{40}Ar in the mixture of gas released upon fusion of a sample. The ^{36}Ar is almost entirely from atmospheric contamination (a small portion is from the tracer); a known amount of ^{38}Ar is added as a tracer, the rest is due to atmospheric contamination. The ^{40}Ar is from the atmosphere, the tracer, and the radioactive decay of ^{40}K.

$$^{36}Ar_M = {}^{36}Ar_A + {}^{36}Ar_T \; ; \text{ where } \quad \begin{aligned} {}^{36}Ar_M &= \text{mixture (total)} \\ {}^{36}Ar_A &= \text{atmospheric} \\ \text{and } {}^{36}Ar_T &= \text{tracer} \end{aligned}$$

$$^{38}Ar_M = {}^{38}Ar_T + {}^{38}Ar_A$$

$$^{40}Ar_M = {}^{40}Ar_{rad} + {}^{40}Ar_A + {}^{40}Ar_T \; ; \text{ where } {}^{40}Ar_{rad} = {}^{40}Ar \text{ produced from decay of } {}^{40}K$$

$$^{40}Ar_{rad} = {}^{38}Ar_T \left\{ \left(\frac{^{40}Ar}{^{38}Ar}\right)_M - \left(\frac{^{40}Ar}{^{38}Ar}\right)_T - \left[\frac{1 - \left(\frac{^{38}Ar}{^{36}Ar}\right)_M \left(\frac{^{36}Ar}{^{38}Ar}\right)_T}{\left(\frac{^{38}Ar}{^{36}Ar}\right)_M \left(\frac{^{36}Ar}{^{38}Ar}\right)_A - 1} \right] \left[\left(\frac{^{40}Ar}{^{38}Ar}\right)_A - \left(\frac{^{40}Ar}{^{38}Ar}\right)_M \right] \right\} ;$$

where $\left(\frac{^{36}Ar}{^{38}Ar}\right)_A$ and $\left(\frac{^{40}Ar}{^{38}Ar}\right)_A$ are constants:

$$\left(\frac{^{36}Ar}{^{38}Ar}\right)_A = 5.35$$

$$\left(\frac{^{40}Ar}{^{38}Ar}\right)_A = 1581$$

and $\left(\frac{^{40}Ar}{^{38}Ar}\right)_T$, $\left(\frac{^{36}Ar}{^{38}Ar}\right)_T$, and $^{38}Ar_T$ are calibrated values for the tracer and are:

$$\left(\frac{^{40}Ar}{^{38}Ar}\right)_T = 1.24 \times 10^{-2}$$

$$\left(\frac{^{36}Ar}{^{38}Ar}\right)_T = 5.56 \times 10^{-6}$$

$$^{38}Ar_T = 2.007 \times 10^{-10} \text{ moles STP/cc}$$

and $\left(\frac{^{40}Ar}{^{38}Ar}\right)_M$ and $\left(\frac{^{38}Ar}{^{36}Ar}\right)_M$ are measured values for the gas mixture.

(The discrimination constant used was 0.9941).

The ratio of $^{40}Ar_{rad}/^{40}Ar_M$ is the fraction of the total ^{40}Ar that is radiogenic and as this fraction gets smaller, the precision of $^{40}Ar_{rad}$ decreases because of the magnification of small errors associated with the measure of the isotopic ratios of atmospheric and trace argon.

This causes relatively large uncertainties in the ratio of $^{40}Ar_{rad}/^{40}K$ which is used in the calculation of the apparent age (t).

$$t = 1.804 \times 10^9 \ \ln\left[9.542\left(^{40}Ar_{rad}/^{40}K\right)+1\right]$$

Therefore, one tries to avoid dating samples which contain phases that contain large amounts of atmospheric argon (e.g., alteration phases such as carbonates and clay, Dalrymple and Lanphere, 1969).

An anomalously young calculated age may be due to loss of $^{40}Ar_{rad}$ from a system which is opened by alteration (including the devitrification of glass) or weathering. An anomalously high age may be due to the presence of ^{40}Ar, either from inclusions of older material in the magma and/or from the presence of a mineral which contains "excess" ^{40}Ar. The former should be considered when dealing with basalts, since volcanic rocks often contain xenoliths. The latter is not as applicable to volcanic rocks, since most "excess" ^{40}Ar has been found in minerals which form in an environment of a high partial pressure of argon. However, olivine can incorporate some "excess" ^{40}Ar (Dalrymple and Lanphere, 1969). The effect of extraneous argon is exaggerated by a low K-content. In a study of 22 historic lava flows (Dalrymple, 1969), $^{40}Ar/^{36}Ar$ ratios were measured to indicate whether "excess" ^{40}Ar was present (the argon isotopic ratios should have been essentially the same as atmosphere). Only three samples had ratios significantly higher than atmosphere, and these all contained ultramafic xenoliths.

Volcanic rocks which contain glass are generally not suitable for dating because the argon retention properties of glasses are not understood. Thus, the grain size of samples used for dating should be large enough to enable microscopic identification of the constituent minerals, especially large enough to determine whether the groundmass is crystalline at all, since it is likely to contain the potassium-bearing phase(s) (Miller and Mussett, 1963).

The potassium analyses of several samples from within a Late Cenozoic basalt flow were made by Dalrymple and Hirooka (1965). Inherent inhomogeneities in K content were indicated, both within a single sample and within the flow. However, when ages were determined, the errors were not significant (in both cases the standard deviation was less than 2%).

PETROGRAPHIC ANALYSIS OF SAMPLES

All of these basalt samples have been classified as alkali olivine basalts. They contain from 5-10 percent euhedral to subhedral olivine phenocrysts ranging in size from approximately 1-3 mm. Rare plagioclase phenocrysts are present. The plagioclase has a composition of about An_{70-75}. The groundmass consists of plagioclase laths (0.03-0.5 mm), olivine (0.01-0.1 mm), clinopyroxene (?), and some interstitial material which seems to be crystalline, though fine-grained. Some of the plagioclase laths are oriented parallel to the margins of the olivine phenocrysts, indicating earlier crystallization of the olivine (Figure 3). However, beyond the neighborhood of the phenocrysts, the plagioclase laths exhibit a sub-parallel orientation (pilotaxitic texture). The potassium contents of these rocks are fairly high for basalts and the visible phases do not normally contain much potassium. The potassium has often been found to reside in the late-crystallizing interstitial material (Miller and Mussett, 1963). There is a large amount of opaque minerals (iron oxides) found in both the olivine phenocrysts and in the groundmass.

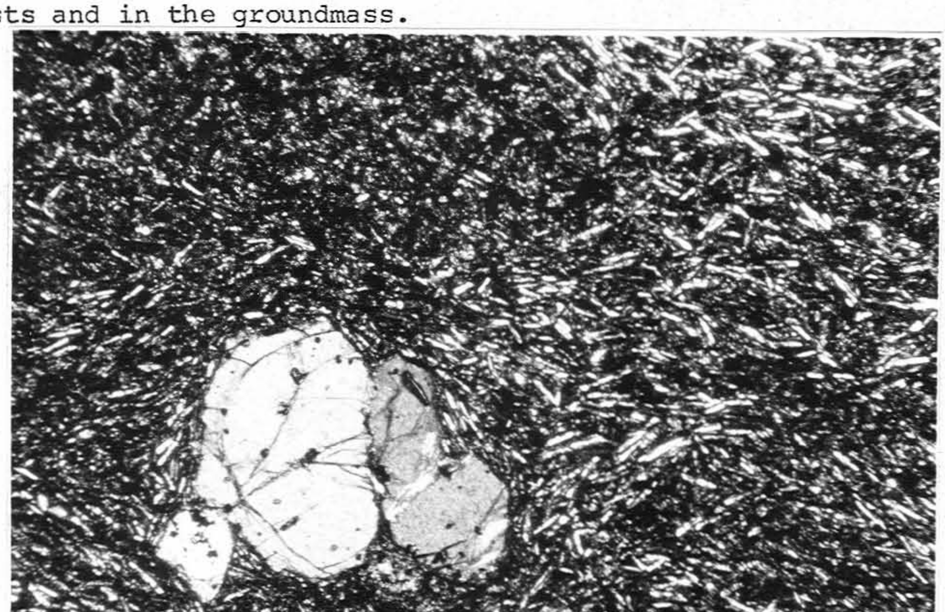

Figure 3

The thin-sections indicated that the samples were very similar, apparently differing only in amount of groundmass olivine and the degree of the oxides' crystallization. Nothing was distinguished in the thin-sections which could be used to predict the subsequent variability of calculated ages within a sample.

TECHNIQUES

SAMPLE COLLECTION

Sample localities were selected after the region of the lava flows was examined and suitable sites were discussed with Wayne Hamilton. Samples from Crater Hill were chosen with reference to a map (Nielson, unpublished Master's thesis, 1976) which differentiates several flows on Crater Hill on the basis of their geomorphologic character (described by Hamblin, 1970). Differential weathering and other criteria were used to establish their apparent relative ages. From oldest to youngest, the flows that were sampled were designated IIA (sample 901-3), IIIA (901-2), and IIIB (901-1) (see Figure 2, with overlay). Two samples were collected from the flow sequence above Grapevine Spring, which is approximately 400 feet thick. One sample was taken near the bottom of the sequence (902-1) and the other near the top (902-2). One sample was collected from a flow at the head of Lee Valley (814-5) and another was collected northwest of Pocket Mesa (814-4).

All samples were obtained from as fresh an outcrop as possible. Obviously altered or weathered material was discarded and extremely vesicular rocks were avoided. Collections were made from the mid-parts (vertically speaking) of the flows in order to obtain the most holocrystalline samples possible.

SAMPLE PREPARATION

Individual samples were crushed and pulverized to maximize the -30 to +60 mesh size fraction. After sieving, the samples were routinely washed in acetone, alcohol, and then distilled water. An aliquant of each sample was split off, treated with a 50% solution of HCl for 10-15 minutes to dissolve amygdaloidal carbonate which can contain a large amount of atmospheric argon, and was then re-washed with distilled water. From this point each sample number actually had two samples associated with it--one treated with HCl and one untreated. Since the grains were too small for mineral separations to be feasible, whole-rock analyses were made in all cases.

To prepare for potassium determination, an aliquant of each sample was ground to -100 mesh and duplicate splits were dissolved and treated according to the method of Cooper (1963). The resulting solutions were analyzed on a Zeiss PF-5 single-channel flame photometer located in the Potassium-Argon Laboratory. The potassium contents are found in Table 1.

The isotopic composition of the argon released by a fused sample plus its tracer was determined with a Nuclide mass spectrometer with 6-inch radius and 60° sector. A sample was placed in the sample bottle in one of two ways.

In the first, high-purity aluminum capsules were filled with -30, +60 mesh size sample and loaded in the side arm of the sample bottle. After evacuation of the extraction and purification system, a fusion blank was run on the sample bottle to drive any occluded atmospheric argon from it. The aluminum capsules containing the sample were then dropped via a quartz funnel into a high-purity molybdenum crucible and the sample plus aluminum melted by induction heating using a Lepel radio-frequency generator. Only 3-4 g of sample could be loaded this way and a great deal of aluminum was deposited on the inner wall of the sample bottle.

The second method bypassed the aluminum packaging and the -30 to +60 mesh sample was loaded directly into the molybdenum crucible before the system was evacuated. About 8-9 g could be loaded this way but no fusion blank could be run prior to the analysis.

These two methods were used to determine what effect fusion blanks, aluminum capsules, and sample size would have on the percentages of radiogenic ^{40}Ar and hence on the samples age and reproducibility.

DATA REDUCTION

The calculated age of a sample was obtained by the selection of the computer-generated curves which gave the best visual fit of the data. Post-1977 constants were used in the calculations (λ=5.543 x 10^{-10} yr^{-10}, $^{40}K/K$=1.167 x 10^{-4} mole/mole, $\lambda_\epsilon/\lambda_\beta$ =0.1171). The error in the calculated age is a function only of analytical precision and is calculated after Cox and Dalrymple (1967).

RESULTS AND CONCLUSIONS

A summary of the techniques and resultant calculated ages for the dated samples is found in Table 1. Since, in this study, each calculated age is compared only with ages from the same sample, the critical value test is not applicable. It is apparent that there were variations in duplicate analyses.

The sample from Crater Hill which was designated 901-3 (IIA, the oldest of the three sampled flows according to Nielson) gave a series of ages of several hundreds of thousands of years. Though not consistent, they indicate an age which is an order or two of magnitude greater than suggested by Threet (1958). The attempt to date the sample 901-2 (IIIA) was unsuccessful, so no attempt was made to date the still younger sample, 901-1 (IIIB). Thus, no evidence can be presented about the time interval between these flows.

The sample from the basal flow at Grapevine Spring (902-1) provided consistent dates between 200,000 and 300,000 years B.P. These ages agree with the estimate of Hamilton (pers. comm., 1977). The attempt to date the sample from the upper part of the flow sequence (902-2) was unsuccessful. Again, it was not possible to estimate the time interval between the early and late flows in Grapevine Wash and North Creek.

The sample from the flow at the head of Lee Valley gives a series of dates, which while not conclusive, provides an approximate magnitude for the age--between 500,000 and 1 m.y.

Treating the sample with HCl had no significant effect on the range of a sample's calculated ages. There is an indication that it gives greater percentages of radiogenic argon and slightly decreased standard

SAMPLE NO.	LOCATION		% K	LOADING TECH	% Ar_r	CALCULATED AGE
814-5	Head of Lee Valley	HCl	1.44127	Pack	17.7	840,000 ± 40,000
				Cruc	18.7	540,000 ± 30,000
		Untr	1.43687	Pack	14.3	650,000 ± 30,000
				Cruc	11.0	770,000 ± 40,000
901-2	Crater Hill III A	HCl	1.04400			
		Untr	1.03530	Pack	1.6	150,000 ± 160,000
901-3	Crater Hill II A	HCl	1.02589	Pack	6.3	490,000 ± 100,000
				Cruc	6.2	350,000 ± 60,000
		Untr	1.04272	Cruc	4.3	510,000 ± 190,000
902-1	Grapevine Spring basal	HCl	2.26330	Pack	8.2	240,000 ± 40,000
				Cruc	8.3	270,000 ± 30,000
		Untr	2.19287	Pack	8.6	300,000 ± 60,000
902-2	Grapevine Spring top	HCl	1.00561	Cruc	2.0	910,000 ± 270,000
		Untr	0.98776	Pack	0.2	90,000 ± 470,000

Table 1 Compilation of K-Ar data

deviations.

There was no discernible effect on either the calculated ages or percentage of radiogenic argon with the sample weight variation from 3-4 g to 8 g. However, systems equipped for routine analysis of Quaternary basalts commonly fuse 30 g of sample (Shaffiqullah, U. of Arizona, pers. comm. to J. F. Sutter, 1978). Perhaps the weight difference in these analyses was not great enough to show significant variations. As stated above, the more radiogenic argon which is present, the more accurate will its measurement be.

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